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# Platte River Hydrologic Research Center

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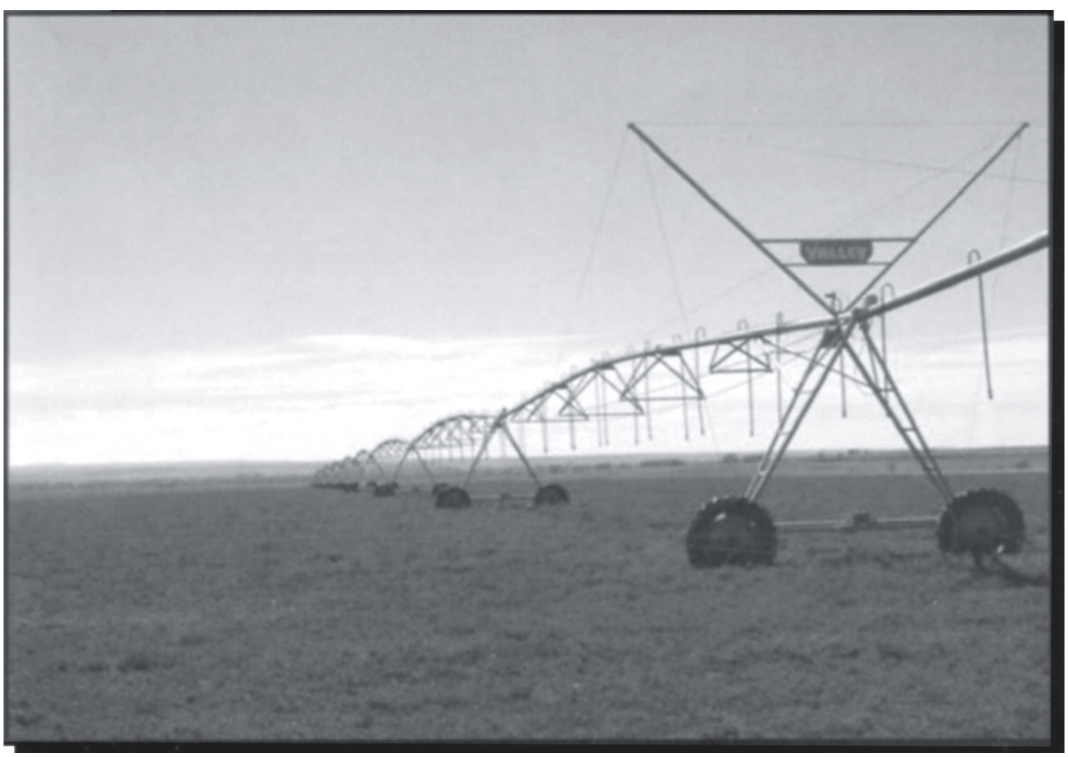
# Hydrology And Well Augmentation In The South Platte River Basin

by

Charles F. Leaf



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# Hydrology And Well Augmentation In The South Platte River Basin [1)]

by

**Charles F. Leaf**

## Abstract

A review of the scientific literature dating back to 1943, and Platte River Basin Water Balance Model© calibrated and validated simulations of the South Platte River reach between Kersey and Julesburg, CO during 1975 - 1994 have yielded the following results:

1. Negative alluvial aquifer storage changes relative to no pumping were assumed to represent encroachment by wells on senior surface water rights. These changes averaged -20,000 af/yr during the 1975-1994 period, and 4 percent of total pumping. This compares with an overall -19,000 af/yr for the 1947-1970 period derived by Hurr, et al. (1975). A frequency analysis of simulated year-to-year storage changes during 1975 - 1994 indicated that the -91,000 af storage change in 1977 - an especially dry year, was a less than 20-year recurrence interval event. This compares with -80,000 af in 2002, which also was a near 20-year recurrence interval event. These storage changes represent only one percent of the total alluvial aquifer storage of approximately 8,500,000 af in this reach of the river, and 20 percent of total pumping.

2. Current augmentation decrees would have required that wells in existence in 2002 have sufficient water in place to replace approximately 250,000 af/yr - each year. As a result, there have been massive well shutdowns in the valley.

3. According to this study, there was apparently no significant hydrologic impact of the wells during November - April during any year. Thus, no encroachment on senior reservoir rights.

4. Glover (1975) and this study which accurately simulated river behavior have shown that lag times in the Kersey to Julesburg reach of the river are short. Thus, it takes but a few years of lead time to establish a new hydrologic regimen. According to Glover (1975), at the end of this short period, "*... a new regimen would have been established and what took place before will have minor importance...*" Because what took place in the river (three or fewer) years earlier has minor significance today, it is gross error to carry forward, by mathematically complex uncalibrated and unvalidated lagging procedures, fictitious depletions from wells that began pumping more than 50 years ago.

**Key Words:** Alluvial Aquifer, Hydrology, Simulation Models, South Platte Endangered Species Recovery Program, South Platte River Basin, Three States Agreement, Water Balance, Water Rights, Water Yield, Well Augmentation, Well Depletions.

[1)] A summary of this paper has been accepted for presentation at the American Water Resources Association 2007 Annual Conference, November 12-15, Albuquerque, New Mexico.

## Introduction

Because the legislative and legal history behind well augmentation in the South Platte River Basin has recently been covered in great detail elsewhere in the media and published literature, it will not be repeated here.  For an in-depth history and coverage of Colorado Water law, the reader is referred to the Colorado water Law Bench Book, published by the *Colorado Bar Association* and Kryloff (2007).

The purpose of this report is to present a technical evaluation of the current application of these new laws and the regulation of wells.  In doing so, the status of knowledge concerning actual river behavior dating back from the early 1940s to the present time has been incorporated into the analysis by means of a comprehensive, yet conceptually simple water yield simulation model.  The results from this model are then compared with the current legal and regulatory requirements that have been imposed on wells, and conclusions are reached as to the validity of these legal requirements and regulations when compared with actual river behavior.

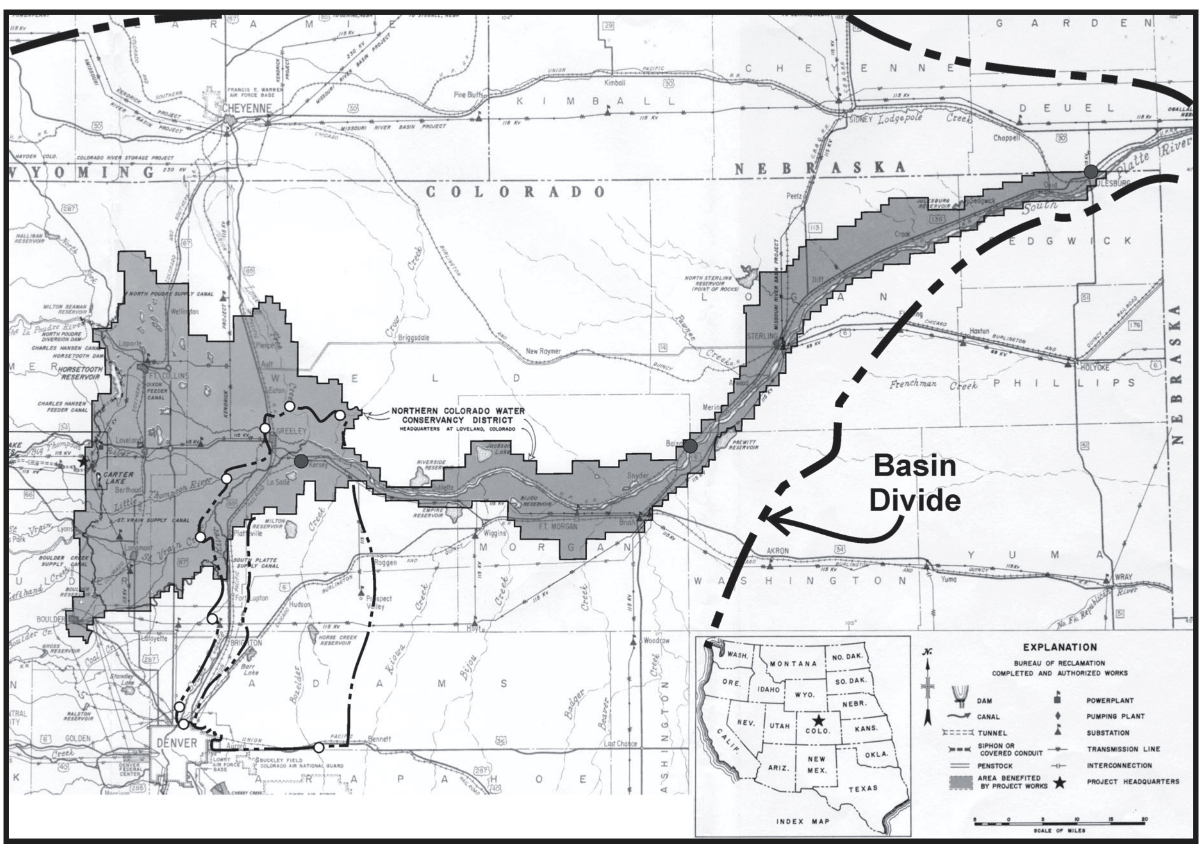
## Early Studies

Perhaps the earliest comprehensive groundwater inventory in the South Platte Valley from Denver to Julesburg (Figure 1) was done by Code (1943).  Some twenty years later, Smith et al. (1964) published a comprehensive study of groundwater resources and hydrology of the South Platte between Denver and Kersey.  Hurr, et al. (1975) published results from the most comprehensive hydrologic study of the South Platte alluvial aquifer to date.

More recently, Leaf (1999) developed the Platte River Basin Water Balance Model © (PRBWBM).  The PRBWBM has been calibrated and validated in the reach between Henderson and Kersey using data presented

**Figure 1 - Location Map**

***See Hurr (1975) for a map showing the areal extent of the alluvial aquifer along the South Platte River downstream from Henderson.***



by Hurr, et al. (1975) and more recent data.

## South Platte River Basin Hydrology

Figure 2, developed by Hurr, et al. (1975) shows an average-year water balance for the Henderson to Julesburg reach of the river based on the 1947 - 1970 period of record. The most significant result in this graphic is a -19,000 af/yr change in storage from a fully recharged alluvial aquifer. By some accounts, total aquifer storage in this reach is approximately 8,850,000 af (Robson, 1989). Hence, the average annual depletion was only 0.2 percent between 1947 - 1970 in spite of the fact that groundwater pumping during that peroid averaged 420,000 af/yr (Figure 2).

It should be noted that water yields have increased in the reach between Denver and Julesburg since the mid-fifties primarily as the result of transbasin imports and increased return flows (Leaf 1998 and Stenzel, 2006). Accordingly, the water balance and particularly the change in alluvial storage shown in Figure 2 was not changed significantly during the 1975 - 1994 record period. Since 1995, however, (1) accelerated changes in irrigation practices (flood irrigation to sprinklers), (2) expansion of the riparian zone, (3) the Cooperative Agreement for Endangered Species Recovery (Dept. of the Interior, 2006), (4) Front Range development, (5) well augmentation, (6) massive well shutdowns, and (7) evolving water rights administration are disrupting the water balance shown in Figure 2.

## Platte River Basin Water Balance Model©

The extensive work by Hurr, et al. (1975) has provided *"the foundation upon which an analysis of the cause-and-effect relationships for proposed changes in water resource management can be made."* The Platte River Basin Water Balance Model© developed by Leaf (1999) builds on the foundation provided by Hurr, et al. (1975).

Figure 3 shows a typical reach of the river in the Platte River Basin. On this figure are the important hydrologic variables necessary to quantify a water balance.

The mathematics used in the PRBWBM for computing both surface and subsurface components of the water balance is given by the equation:

$$Q_{dn} = Q_{np} + Q_{si} - Q_{sd} + \propto (Q_{gd} + Q_{sd}) - Q_{gd} - Q_{se} + Q_{cs} + Q_{rs} + Q_{nr} \pm \Delta_s \qquad [1]$$

where

$Q_{dn}$ = water yield at downstream node,

$Q_{up}$ = water yield at upstream node,

$Q_{si}$ = surface inflow between upstream and downstream nodes,

$Q_{sd}$ = surface water diversions,

$\propto$ = irrigation return flow coefficient,

$Q_{gd}$ = groundwater diversions,

$Q_{se}$ = evaporation from surface water sources,

$Q_{cs}$ = canal seepage,

$Q_{rs}$ = seepage from reservoirs and natural bodies of water,

$Q_{nr}$ = natural recharge from precipitation and

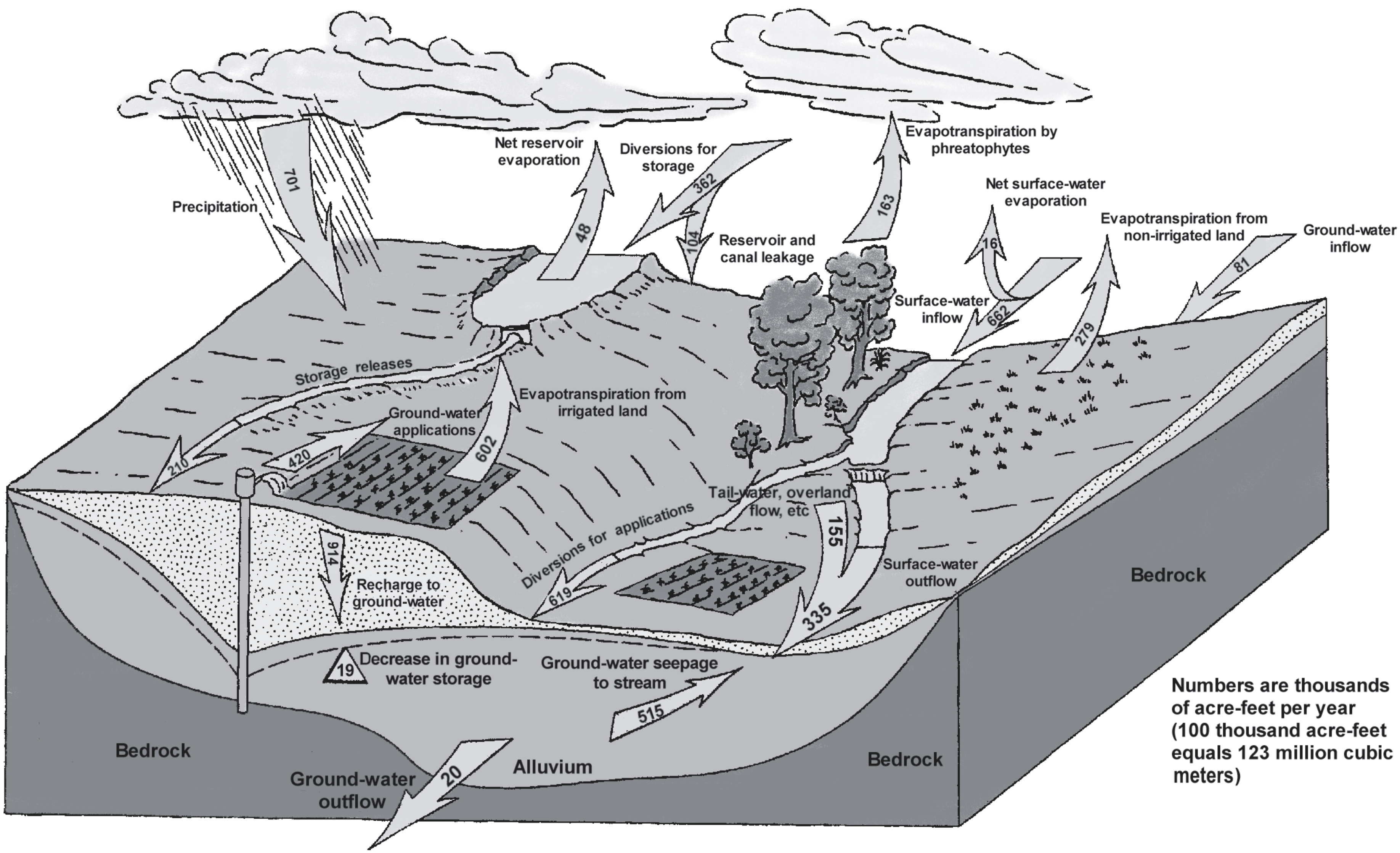
$\Delta_S$ = change in storage

The water balance can be computed on a monthly, seasonal, or annual basis.

In most cases, explicit quantification of all terms in equation [1] is not possible. Accordingly, several terms must be combined and determined as a residual in the computation of a reach water balance. For the reach of the South Platte River between Kersey and Julesburg (Figure 1), $\Sigma(Q_{cs} + Q_{rs} + Q_{si} + Q_{nr} - Q_{se})$ are included as one term in the water balance calculations. The irrigation return flow coefficient, $\propto$ is assumed to be 0.45 after Hurr et al. (1975).

Leaf (1999) calibrated the PRBWBM to the Henderson-Julesburg reach using the 1947 - 1970 data base. Validation was done for 1975 - 1994. Simulations of the year-to-year water balance for the Kersey to Julesburg reach are plotted in Figure 4. Goodness of fit analyses between observed and simulated water yields in Figure 4 are presented in Table 1 (A) Appendix I for quantification of the variables in equation [1]. Data sources for quantification of the variables in Equation [1] and plotted and Figure 4 include published data by the Colorado State Engineer, U.S. Geological Survey, Natural Resource Conservation Service, Dille (1960), and Glover (1975).

**Figure 2 - Average Annual Water Budget, 1947 - 1970 for South Platte River Between Henderson And Julesburg, CO (Hurr, et al. 1975)**




Numbers are thousands of acre-feet per year (100 thousand acre-feet equals 123 million cubic meters)

**Figure 3**

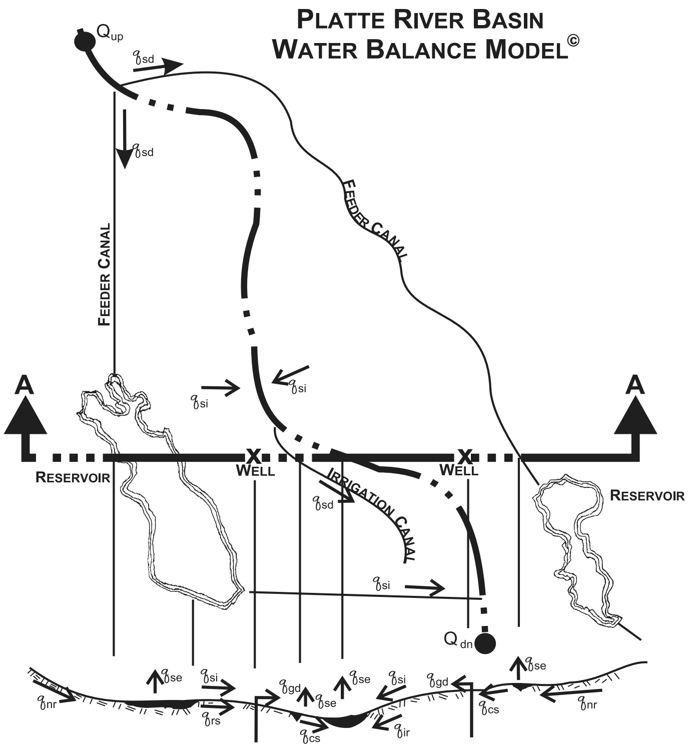



**Figure 4**
**Comparison of Observed vs. Simulated Water Yields at Julesburg, CO**

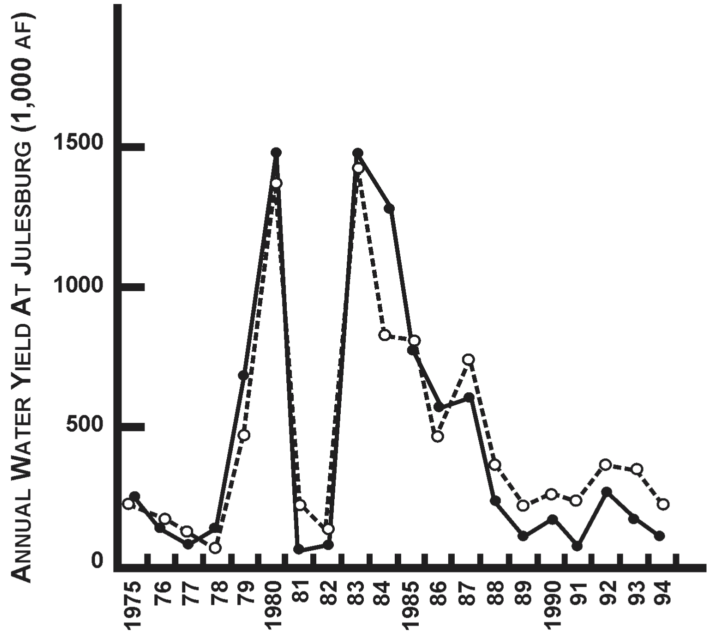



**Table 1 - Estimated Depletions Due to Pumping in the Reach of the South Platte River Between Kersey and Julesburg (Glover, 1975)**

| Month (1) | Estimated Depletion Acre-feet (2) | Percent Annual (3) | Cubic Feet per Second (4) | Pumping Pattern [2)] (5) |
|---|---|---|---|---|
| January | 18,900 | 7.103 | 313 | 0 |
| February | 16,800 | 6.313 | 278 | 0 |
| March | 15,500 | 5.825 | 257 | 0 |
| April | 13,700 | 5.148 | 227 | 0 |
| May | 15,700 | 5.900 | 260 | 0.08 |
| June | 19,100 | 7.178 | 316 | 0.12 |
| July | 23,400 | 8.794 | 388 | 0.23 |
| August | 30,900 | 11.612 | 512 | 0.30 |
| September | 34,600 | 13.003 | 573 | 0.20 |
| October | 30,600 | 11.499 | 507 | 0.07 |
| November | 25,500 | 9.583 | 422 | 0 |
| December | 21,400 | 8.042 | 354 | 0 |
| Total | 266,100 | 100.00 | | 1 |

[2)] From unpublished USBR data.

## Basin Lag Times

Basin depletions and returns were lagged to the river according to the time distribution shown in Table 1. This distribution was derived by Glover (1975). Month-to-month simulations of key elements in the water balance for the average year are plotted in Figure 5. The simulated hydrograph in Figure 5 was obtained by merely adding and subtracting ordinates. Table 2 presents the simulated water balance shown in Figure 5.

The reasonable agreement between the observed and simulated average annual hydrograph at Julesburg is obvious (see Table 2 (A), Appendix I). The simulation in Figure 5 shows that by and large, it takes but a few years of lead time to establish a new regimen in the river. It is interesting that Glover (1975) also concluded that at the end of this short period of time, *"... a new regimen will have been established* ***and what took place before will have minor importance..."*** on river behavior.

## Injury

While not an explicit quantification of the hydrologic impact of wells, it is entirely reasonable to assume that the change in storage $\Delta s$, is a reliable indication of this impact. Consistent with Hurr, et al. (1975), the simulated average annual change in storage is approximately -20,000 af/yr. As seen in Figure 5, aquifer storage reductions take place during the months of May through October during the average year. The largest changes in storage occur during July through September, precisely when single-source and supplemental water supplies from groundwater are most needed. It has been argued that the negative changes in storage have encroached upon senior surface water rights, thus causing injury to these rights.

The annual occurence and magnitude of these changes will be discussed next.

## Year-To-Year Changes In Aquifer Storage Due To Pumping

Glover (1975) emphasized that Colorado Water Law requires that junior pumpers restore the river to what it would have been had there been no pumping. This hydrologic impact can be obtained by: (a) simulating the water balance without the wells ($Q_{gd}$ in equation [1]), (b) simulating the water balance with the wells, and calculating the difference only during those months when simulated flows at Julesburg are negative which indicates a reduction in storage. This technique has often been used to quantify hydrologic impacts (see Leaf, 1974, Forrester, 1961, and Wright Water Engineers and Leaf, 1986).

The monthly change in storage, $\Delta s$, attributed to well pumping was calculated for each year in the 1975 - 1994 record period by equations [2] through [4] below.

$$\Delta s_w = Q_{dn1} + Q_{dn2} \qquad [2]$$

where

$$Q_{dn1} = Q_{up} - Q_{sd1} - Q_{gd1} + \propto (Q_{gd1} + Q_{sd1}) + \Sigma (Q_{si} - Q_{se} - Q_{cs} - Q_{rs} + Q_{nr}) \qquad [3]$$

and

$$Q_{dn2} = Q_{up} - Q_{sd2} - Q_{gd2} + \propto (Q_{gd2} + Q_{sd2}) + \Sigma (Q_{si} - Q_{se} - Q_{cs} - Q_{rs} + Q_{nr}) \qquad [4]$$

In equation [2] above,

$\Delta s_w$ = the change in groundwater storage attributed to wells,

and

all other terms are as defined below in equation [1].

Table 3 summarizes the simulated monthly hydrologic impacts of the wells. The impacts are expressed as *"Replacement Water Requirements"* assuming that the quantities summarized actually encroached on senior surface water rights. The results in Table 3 are plotted in Figure 6. Also plotted for comparison are monthly estimates of lagged annual groundwater consumptive use from all of the wells which averaged some 248,000 af/yr.

At least two significant results have emerged from Table 1 and the comparison shown in Figure 6 for the 1975 - 1994 record period:

1. The hydrologic impact of groundwater diversions in the entire reach of the South Platte River

between Kersey is less than 15 percent of the lagged consumptive use from total well pumping (-31,400 af/yr vs. -248,000 af/yr)[3] or 7 percent of total pumping. Assuming 8,850,000 af of alluvial aquifer storage, the hydrologic impact of the wells is a 0.3 percent of total storage.

2. Well pumping has had virtually no impact on the river during the months of November through April.

## Frequency Analysis

Because a wide year-to-year variation exists in replacement requirements, a frequency analysis was made of the annual totals in Table 1. Results from this analysis are plotted in Figure 7. Also plotted for reference are hydrologic impacts of the simulated wells in 2002, the most recent severely dry year, and also for 1935, assuming that all wells that existed in 2002 had pumped. As seen in Figure 6, 2002 had a recurrence interval of 10 years and 1935 approximately 20 years. Also plotted in Figure 7 is the level of replacement water well users would be required to have in place each year in order to continue pumping at historic levels. This information was obtained from a survey of court-decreed replacement water requirements which indicated that for some 4,000 wells that existed in 2002, almost 250,000 af of groundwater consumptive use would have been required each year to pump at historic levels (Figure 8). Augmentation plans for the approximately 2,000 wells currently pumping, require a 50-year recurrence interval supply of water to be in place each year for these wells to pump at historic levels.

**Figure 5 - Average Year Water Yield Simulation of the South Platte River Between Kersey and Julesburg 1975 - 1994**

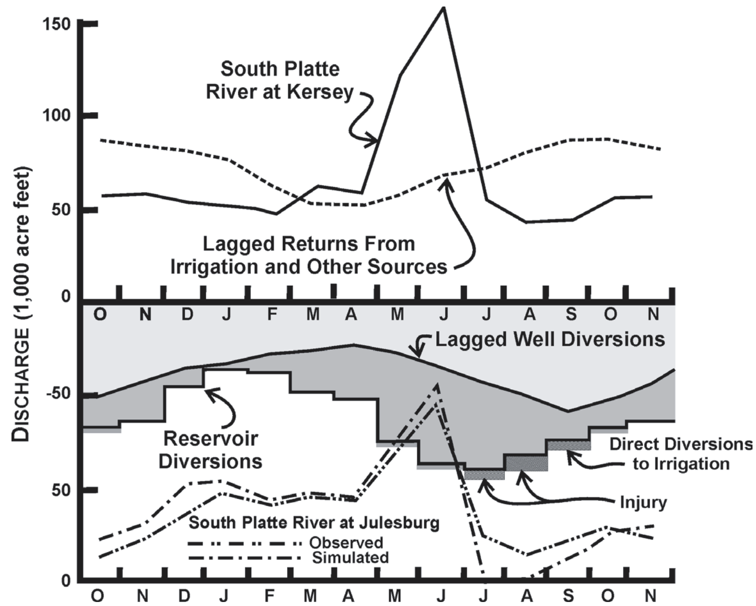
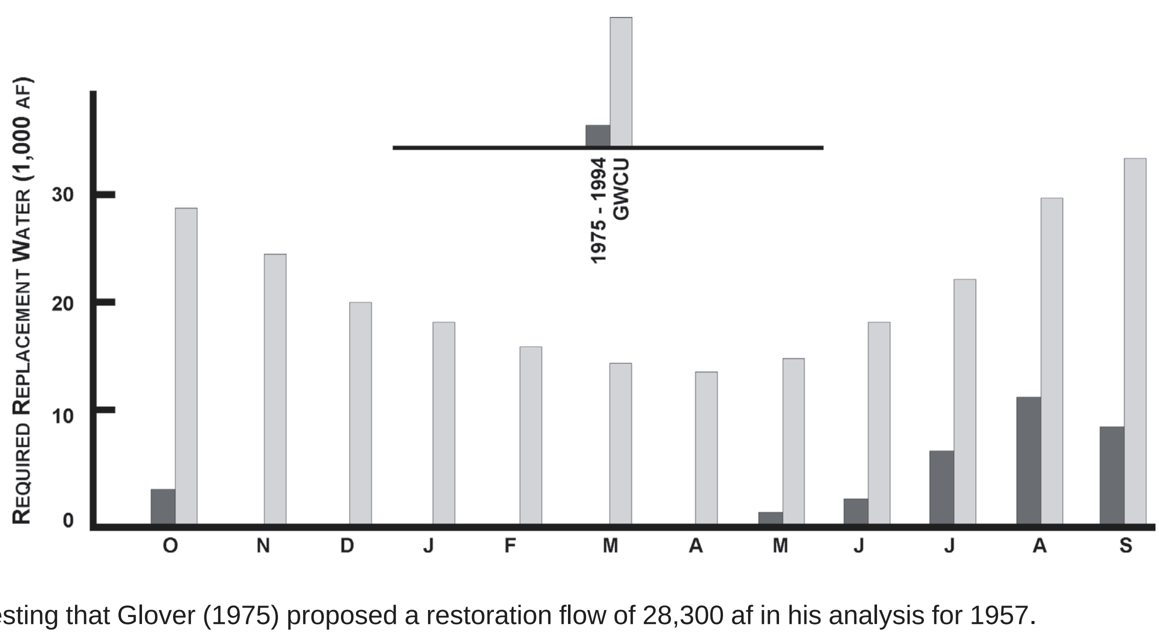



**Figure 6 - Comparison of Simulated Average Annual Replacement Water Requirements for 1975 - 1994 With Total Groundwater Consumptive Use (GWCU)**




[3] It is interesting that Glover (1975) proposed a restoration flow of 28,300 af in his analysis for 1957.

## Table 2 - Water Yield Simulation of the South Platte River Between Kersey and Julesburg: With Wells and Without Wells Comparison for Average Year 1975 - 1994 (1,000 af)

| | | O | N | D | J | F | M | A | M | J | J | A | S | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) | (15) |
| [8] | Diversions To Storage With Wells | -69.4 | -66.2 | -46.1 | -34.3 | -35.6 | -48.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -299.6 |
| [9] | Diversions To Irrigation With Wells | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | -50.2 | -75.2 | -89.8 | -95.6 | -89.8 | -71.7 | -472.2 |
| [10] | Well Diversions | -52.6 | -43.6 | -36.6 | -32.3 | -28.7 | -26.6 | -23.4 | -26.8 | -32.7 | -40.1 | -49.3 | -59.2 | -451.9 |
| [11] | Total | -122.1 | -109.8 | -82.7 | -66.6 | -64.3 | -74.5 | -73.6 | -102.0 | -122.6 | -135.6 | -139.1 | -130.9 | -1223.8 |
| [12] | Irrigation Returns With Wells | 62.6 | 58.9 | 54.9 | 49.4 | 37.2 | 30.0 | 29.0 | 33.5 | 33.1 | 45.9 | 55.1 | 61.0 | 550.7 |
| [13] | Returns From Other Sources | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 312.0 |
| [13a] | Total Returns | 88.6 | 84.9 | 80.9 | 75.4 | 63.2 | 56.0 | 55.0 | 59.5 | 59.1 | 71.9 | 81.1 | 87.0 | 862.7 |
| [14] | Simulated S. Platte River @ Julesburg | 19.8 | 31.0 | 51.2 | 59.7 | 48.3 | 41.9 | 39.3 | 80.3 | 95.7 | -8.0 | -16.1 | 1.9 | 444.9 |
| [15] | Observed S. Platte River @ Julesburg | 25.6 | 23.4 | 32.9 | 50.2 | 50.1 | 44.3 | 42.0 | 75.9 | 60.8 | 21.3 | 12.5 | 23.1 | 462.3 |

## Table 3 - Simulated Replacement Water Requirements in the Kersey To Julesburg Reach of the South Platte River (1,000 af)

| Year | O | N | D | J | F | M | A | M | J | J | A | S | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1975 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 76 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 6.4 | 0.0 | 0.0 | 6.4 |
| 77 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 7.4 | 16.4 | 12.8 | 28.9 | 25.1 | 90.6 |
| 78 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.7 | 10.2 | 9.5 | 21.4 |
| 79 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 10.1 | 10.1 |
| 1980 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.9 | 6.7 | 9.6 |
| 81 | 25.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 9.3 | 21.8 | 31.5 | 31.1 | 118.7 |
| 82 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 26.1 | 8.4 | 34.5 |
| 83 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 84 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 1985 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.2 | 0.0 | 3.2 |
| 86 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 87 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.8 | 15.8 | 21.6 |
| 88 | 4.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 3.9 | 12.0 | 21.0 |
| 89 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.8 | 6.0 | 16.8 | 25.1 | 16.9 | 70.6 |
| 1990 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.1 | 11.5 | 23.9 | 16.2 | 52.7 |
| 91 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 7.5 | 18.4 | 8.6 | 34.5 |
| 92 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 9.6 | 0.0 | 6.4 | 16.0 |
| 93 | 26.9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 8.3 | 16.0 | 0.0 | 51.2 |
| 94 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 7.3 | 5.8 | 18.6 | 15.0 | 18.3 | 65.0 |
| **Mean** | 2.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | 1.9 | 5.8 | 10.5 | 9.3 | 31.4 |
| **Std. Dev.** | 7.98 | | | | | | | 2.52 | 4.30 | 7.22 | 11.42 | 9.13 | 33.62 |

## Discussion And Conclusions

The current regulation of wells in the South Platte River Basin is by no means consistent with the scientific literature. The literature, including this study, has shown that a requirement that wells in existence in 2002 have in place each year a 50-year recurrence interval supply of water each year to augment depletions is not realistic (see Figures 7 and 8).

In 2002, one of the driest years in the past fifty, the apparent encroachment by wells was approximately -80,000 af (Figure 7). It should be noted that according to available data, Groundwater appropriators of the South Platte (GASP) and Central Colorado Water Conservancy District (Central) had the combined capacity to very nearly meet a need of this magnitude during the driest years with modest recharge and surface water supplies (Leaf, 2002). Today, GASP has been eliminated and Central is on the verge of being eliminated.

In addition to the quantity of replacement water that is necessary to restore the river, at least two other issues have emerged. First is the issue of apparent well depletions and consequent encroachment during November-April on senior reservoir rights. According to this study, there is apparently no significant hydrologic impact of the wells during the winter months (Table 3).

The final issue concerns lag times in the basin. It is worth referring to Glover (1975) again who found that it takes but a few years of lead time to establish river regimen, and at the end of this short period, *"... a new regimen will have been established* ***and what took place before will have minor importance..."***

The PRBWBM, which has been extensively calibrated and validated in this study and in Leaf, 1999, supports Glover's conclusions. The simple lagging algorithms shown in Figure 5 correctly simulate overall river behavior with reasonable statistical accuracy as shown by the error analyses in Appendix I.

Since what took place in the river three (or fewer) years earlier has minor significance today, it is gross error to carry forward by mathematically complex uncalibrated and unvalidated lagging procedures, fictitious depletions from wells that began pumping more than 50 years ago.

**Figure 8 - Replacement Water Requirements vs. Number of Wells in Augmentation Plan**

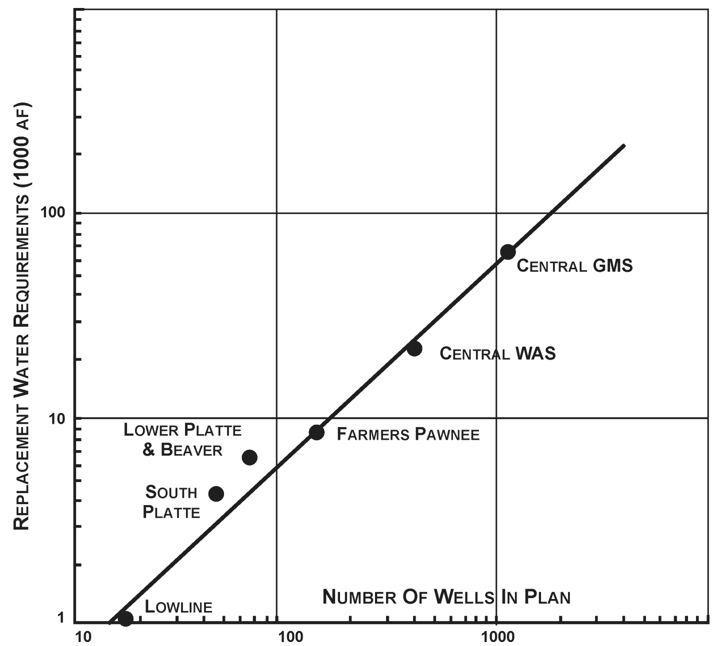
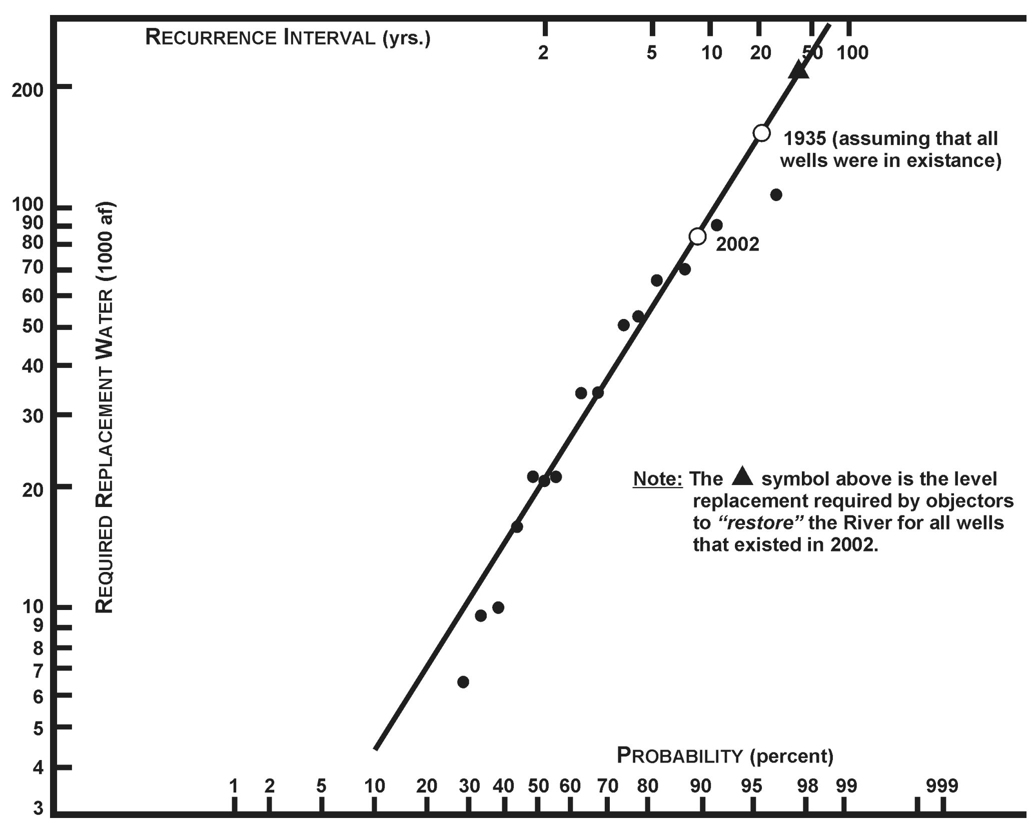



**Figure 7**
**Simulated Replacement Water Requirement Frequency Curves for 1975 - 1994 Record Period in the Kersey-Julesburg Reach of the South Platte River**



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# Appendix I

The ASCE Task committee on Definition of Criteria for Evaluation of Watershed Models of the Watershed Management Committee, Irrigation and Drainage Division (ASCE Task Committee, 1993) has recommended the use of several goodness-of-fit criterion for evaluating model performance. The deviation of runoff volumes $D_V$, is one of the more simple tests and is computed as follows:

$$D_V (\%) = \frac{V-V'}{V} \times 100 \qquad [1A]$$

where V = the measured annual or seasonal runoff volume, and

V' = the model computed annual or seasonal runoff volume.

The second basic goodness-of-fit criterion is the Nash-Sutcliffe coefficient, $R^2$, expressed as:

$$R^2 = 1 - \frac{\sum_{1=1}^{n} (Q_i - Q'_i)^2}{\sum_{1=1}^{n} (Q_i - Q)^2} \qquad [2A]$$

In equations [1A] and [2A] above, $D_V$ = O and $R^2 = 1$, would indicate a perfect fit respectively.

In equation [2A], if $R^2 = 0$, the model is doing no better than using the average of the observed runoff. $R^2 = 1$ denotes perfect agreement between observed and simulated values.

Table 1 (A) summarizes computations of $D_V$ and $R^2$ for the South Platte River at Julesburg for the 1947-1970 calibration period. Calculations of $D_V$ for the 1975-1994 validation period are summarized in Table 2 (A).

## Table 1 (A)

**Computation of: (1) Deviation to Runoff Volume, $D_V$ and**
**(2) Nash-Sutcliffe Coefficient for Simulated 1975 - 1994 Annual Water Yield at Julesburg, CO**

| Year | V | V' | V-V' | (V-V')$^2$ | (V-$\overline{V}$) | (V-$\overline{V}$)$^2$ | $D_V$ (%) |
|---|---|---|---|---|---|---|---|
| 1975 | 255.4 | 255.1 | 0.3 | .09 | -205.66 | 42296.04 | 0.12 |
| 76 | 161.8 | 140.3 | 21.5 | 462.25 | -299.26 | 89556.55 | 13.29 |
| 77 | 110.2 | 83.2 | 27.0 | 729.00 | -350.86 | 123102.74 | 24.50 |
| 78 | 72.4 | 144.7 | -72.3 | 5227.29 | -388.66 | 151056.60 | -99.86 |
| 79 | 474.5 | 634.3 | -219.8 | 48312.04 | 13.44 | 180.14 | -46.32 |
| 1980 | 1369.8 | 1472.5 | -102.7 | 10547.29 | 908.74 | 825808.39 | -7.50 |
| 81 | 232.7 | 64.2 | 168.5 | 28392.25 | 2378.19 | 5655787.68 | 72.41 |
| 82 | 138.6 | 86.0 | 52.6 | 2766.76 | -322.46 | 103980.45 | 37.95 |
| 83 | 1433.1 | 1478.1 | -45.0 | 2025.00 | 972.04 | 944861.76 | -3.14 |
| 84 | 832.7 | 1292.7 | -460.0 | 211600.00 | 371.64 | 138116.29 | -55.24 |
| 1985 | 802.6 | 797.0 | 5.6 | 31.36 | 341.54 | 116649.57 | .70 |
| 86 | 496.0 | 588.5 | -92.5 | 8556.25 | 34.94 | 1220.80 | -18.65 |
| 87 | 740.7 | 601.6 | 139.1 | 19348.81 | 279.64 | 78198.53 | 18.78 |
| 88 | 392.8 | 239.0 | 153.8 | 23654.44 | -68.26 | 4659.43 | 39.15 |
| 89 | 211.9 | 102.1 | 109.8 | 12056.04 | -249.16 | 62080.70 | 51.82 |
| 1990 | 266.6 | 192.1 | 74.5 | 5550.25 | -194.46 | 37814.69 | 27.94 |
| 91 | 264.3 | 83.3 | 181.0 | 32761.00 | -196.76 | 38714.50 | 68.48 |
| 92 | 370.9 | 295.1 | 75.8 | 5745.64 | -90.16 | 8128.82 | 20.44 |
| 93 | 359.4 | 181.5 | 177.9 | 31648.41 | -101.66 | 2033.20 | 49.50 |
| 94 | 234.8 | 120.8 | 114.0 | 12996.00 | -226.26 | 51193.59 | 48.55 |
| **Total** | | | | **462410.17** | | **8475440.97** | |
| **Mean** | **461.06** | | | | | | **12.15** |
| **Std. Dev.** | **389.34** | | | | | | **43.14** |

$$R^2 = 1 - \frac{462410.17}{8475440.97} = 1 - .0546$$

$R^2 = .9454$
$R = .9723$

## Table 2 (A)

### Computation of: (1) Deviation to Runoff Volume, $D_V$ and (2) Nash-Sutcliffe Coefficient for Simulated 1975 - 1994 Mean Water Yield at Julesburg, CO

| Month | V | V' | V-V' | $(V-V')^2$ | $(V-\bar{V})$ | $(V-\bar{V})^2$ | $D_V$ (%) |
|---|---|---|---|---|---|---|---|
| Oct | 25.6 | 19.8 | 5.8 | 33.64 | -14.58 | 212.58 | 22.66 |
| Nov | 23.4 | 31.0 | -7.6 | 57.76 | -16.78 | 281.57 | -32.48 |
| Dec | 32.9 | 51.2 | -18.3 | 334.89 | -7.28 | 53.00 | -55.62 |
| Jan | 50.2 | 59.7 | -9.5 | 90.25 | 10.02 | 100.40 | -18.92 |
| Feb | 50.1 | 48.3 | 1.8 | 3.24 | 9.92 | 98.41 | 3.59 |
| Mar | 44.3 | 41.9 | 2.4 | 5.76 | 4.12 | 16.97 | 5.42 |
| Apr | 42.0 | 39.3 | 2.7 | 7.29 | 1.82 | 3.31 | 6.43 |
| May | 75.9 | 80.3 | -4.4 | 19.36 | 35.72 | 1275.92 | -5.80 |
| Jun | 80.8 | 95.7 | -14.9 | 222.01 | 40.62 | 1649.98 | -18.44 |
| Jul | 21.3 | 0 | 21.3 | 453.69 | -18.88 | 356.45 | 100.00 |
| Aug | 12.6 | 0 | 12.6 | 158.76 | -27.58 | 760.66 | 100.00 |
| Sep | 23.1 | 1.9 | 21.2 | 449.44 | -17.08 | 291.73 | 91.77 |
| **Total** | | | | **1836.09** | | **5100.98** | |
| **Mean** | **40.18** | **39.08** | | | | | **16.55** |
| **Std. Dev.** | **21.53** | **30.81** | | | | | **52.75** |

$$R^2 = 1 - \frac{1836.09}{5100.98} = 1 - 0.362 = 0.640$$

$$R = 0.800$$